Climate Change

An update of recent research from the Hadley Centre

Summary

- Global average temperature in 1999 was lower than in the record-breaking year of 1998, but 1999 was still the fifth warmest year since global records began in 1860.

- Over the last 100 years, warming has been accompanied by a reduction in the frequency of frosts, and an increase in the number of heatwaves, in many parts of the world. The number of days of heavy rain is increasing in some countries.

- Comparison of the observed patterns of warming with model-simulated patterns of warming resulting from natural and man-made factors, indicates that over the last 50 years most of the observed change can be explained by human activities, mainly production of CO_2 from burning fossil fuels.

- Based on the recent IPCC scenarios of future emissions, the Hadley Centre predicts a global warming over the next 100 years of between 2 °C and 4 °C. Warming over land is expected to be some 80% faster than over sea; the highest emission scenario would lead to an almost 6 °C rise over land by 2100.

- Uncertainties in estimates of temperature rise remain high, but poorly quantified. The use of hundreds of different, but plausible, climate models will enable a proper statistical estimate of uncertainty to be built up, which (unlike the current IPCC 1.5 °C to 4.5 °C) can be used in risk assessments.

- Climate change will disrupt the large natural cycle of carbon dioxide between atmosphere, ocean and land. This is the first time that we have included this interaction in a climate model, and find that CO_2 in the atmosphere rises much faster, leading to approximately 40% greater warming. Although the results are not definitive, they do show the potential of this feedback to accelerate warming. The temperature increases given above do not include this effect.

- Planting trees ('Kyoto forests') will absorb CO_2 from the atmosphere. However, in some parts of the world, climate change may lead to less rapid tree growth, or even die back, and hence less uptake of CO_2, than envisaged.

- Because trees are usually darker than the underlying surface (especially snow), they will absorb more sunlight than areas with no trees and hence act to warm the planet. Therefore the beneficial effects on climate of their carbon uptake could be reduced (and, in some areas, reversed) by their darkening effect.

- Although subject to the same gross uncertainties as global climate models, regional climate models provide better detail by taking account of mountains and coasts which are poorly represented in the global model. The Hadley Centre plans to develop a regional climate model that could be run for any area of the world on a PC, as input to vulnerability and adaptation assessments.

Introduction

The Hadley Centre

The United Kingdom government (mainly through the Department of the Environment, Transport and the Regions (DETR)) supports research into the scientific issues surrounding climate change and its impacts. The Hadley Centre for Climate Prediction and Research (part of the Met Office) provides a focus for research into the science of climate change in the United Kingdom.

The primary objective of the Hadley Centre is to provide an up-to-date expert assessment of natural and anthropogenic changes in global and regional climate. Currently, the Centre supports around 100 staff and has access to two Cray T3E supercomputers. A large proportion of staff are involved in national and international collaborations, and many play a role in the activities of the World Climate Research Programme. A number of Hadley Centre staff are contributing to the forthcoming Intergovernmental Panel on Climate Change (IPCC) third assessment report, including eight lead authors.

The specific aims of the Hadley Centre for Climate Prediction and Research are:

- to understand physical, chemical and biological processes within the climate system and develop state-of-the-art climate models which represent them;
- to use the models to simulate climate variability and change over the last 100 years and predict change over the next 100 years;
- to monitor global and national climate variability and change;
- to attribute recent change in climate to specific factors;
- to understand, with the aim of predicting, natural interannual to decadal variability of climate.

In this report

Recent observations of surface temperature continue to show a sizeable warming. On page 5 of this report we provide new results attempting to answer the question 'what is responsible for the temperature increase during the 20th century?'

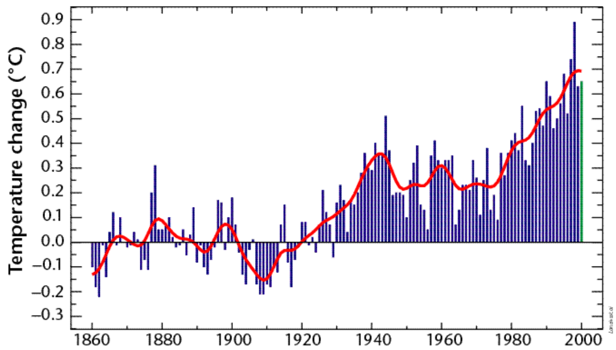
In previous Hadley Centre/DETR reports (presented at CoP 3, 4 and 5) we have shown predictions of the climate change that may result from either the early IPCC business-as-usual emissions scenarios or idealised stabilisation scenarios. On pages 6–10 of the current report we present predictions of the future climate change that may result from a very recent set of emissions scenarios, produced for the IPCC and reported in the Special Report on Emissions Scenarios (SRES). As we shall discuss, these new scenarios have a number of advantages over the earlier business-as-usual scenarios. These predictions have been made with the latest Hadley Centre coupled ocean-atmosphere model, HadCM3.

The only scientifically credible tool for predicting future changes in climate is the general circulation model, usually known as a GCM. This uses a set of mathematical relationships which represent the major processes in the climate system. The three-dimensional ocean–atmosphere models developed at the Hadley Centre predict changes that vary with location and in time. During the past few years the complexity of this type of model has increased considerably as growing computer power has allowed more-elaborate representations of the components of the climate system, and as scientific understanding of climate processes has improved. We are now at a stage where we can produce predictions that take into account the physical behaviour of the climate system and also treat the major chemical processes, such as the sulphur cycle, and even some of the biological processes, such as those which contribute to the carbon cycle. These predictions represent plausible outcomes but have a significant level of uncertainty associated with them. On pages 11–13 we discuss the results of new research linking the physical climate system to the biosphere.

GCMs can predict patterns of climate change, but only down to scales of a few hundred kilometres. On pages 14–17, we report on the use of regional climate models to downscale the global climate predictions to smaller spatial scales.

Recent climate change

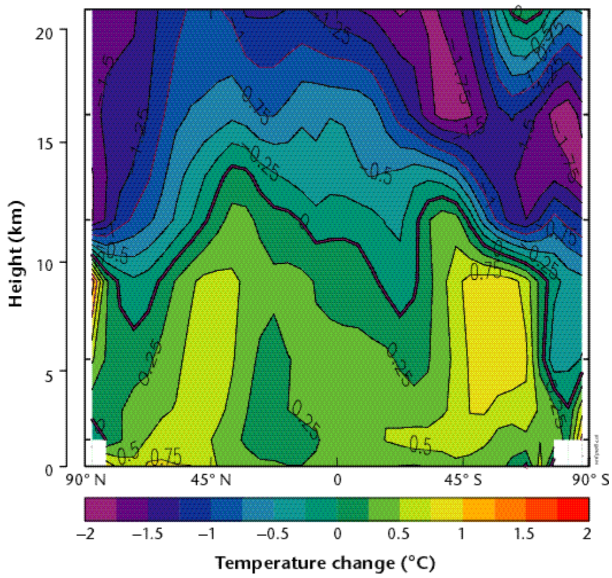
The global mean surface temperature was lower in 1999 than in the record warm year of 1998 (below), mainly because temperatures in the tropical Pacific changed from the warm El Ni o state to the colder La Ni a state. Nevertheless, 1999 was the fifth warmest year since the beginning of the instrument temperature record (1860), and the 1990s was the warmest decade during this period (around 0.6 °C above the temperature during the late 19th century). The temperature shown for 2000 only includes data up to August. Over the continents, the night-time temperatures generally warmed more than those during the day, reducing the daily temperature range. Proxy measurements (such as tree rings and coral) indicate that the temperatures observed over the past decade are higher than any which have occurred during the last 1,000 years.



Observed global average surface temperature rise (°C) from 1860 to August 2000.

The cooling between 1998 and 1999 illustrates that, even when there is a strong long-term warming trend, sizeable year-to-year changes, in either direction, can occur as a result of natural processes within the climate system; it does not negate long-term trends.

Temperature changes in the atmosphere continue to be a topic of debate. Measurements made using balloons and satellites both suggest that the lower layers of the atmosphere (between approximately 1 km and 8 km) have warmed, but that the warming trend is lower than at the surface. This difference could be due to either instrument uncertainties or a real physical mechanism; this is an area of active research. In the stratosphere, between approximately 12 km and 50 km, the measurements show a cooling trend (above, right); this is expected and is partly due to increasing greenhouse gas concentrations, increases in water vapour, and also the depletion of stratospheric ozone.



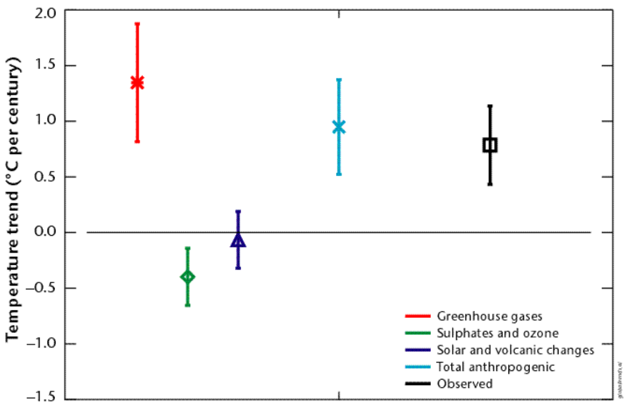
Observed changes in the temperature of the atmosphere (°C) up t 20 km between the period 1965–74 and the 1990s.

The general warming trend has been accompanied by an increase in the number of heatwaves and a reduction in the frequency of frosts in many parts of the world. There are also indications that globally we are experiencing more days with heavy rainfall.

Causes of climate change

We have already seen that the global average surface temperature is now around 0.6 °C warmer than during the middle of the 19th century, an increase that is greater than can be explained by natural variability. To what can we attribute this warming?

The latest Hadley Centre climate model has been used to generate patterns of climate change (which evolve in time) for a range of potential forcing agents: human made emissions of greenhouse gases, sulphur and ozone; changes in natural volcanic aerosols and solar output. A statistical technique was then used to combine the model patterns of each agent in order to produce the best fit to the observed pattern of warming. For each agent, the contribution to the global mean temperature change was estimated. An important feature of the method is that it does not matter if the climate model under- or over-predicts the magnitude of either a particular forcing or the climate response to a particular forcing, as long as the patterns of response are faithfully reproduced. The figure below shows the estimated attribution of climate change to the different forcing agents in the second half of the 20th century using this technique.

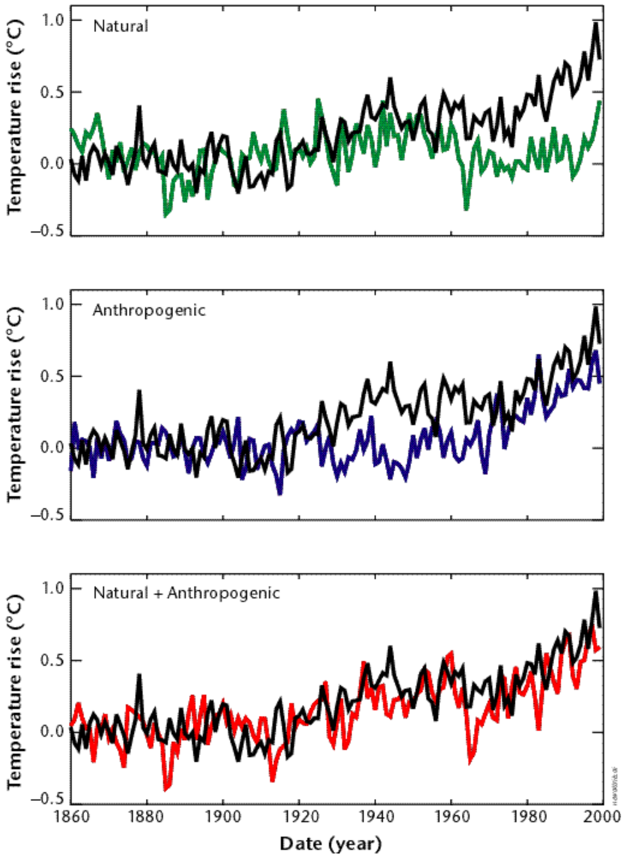


Comparison of observed and simulated global mean temperature trends (°C per century) during the second half of the 20th century for a range of climate-forcing factors.

In the first half of the century, greenhouse gases and, to a much lesser extent, changes in natural forcings (mainly solar output) combine to produce the observed changes. During the second half of the century, the observed warming can be explained by a combination of the changes in greenhouse gases, sulphate aerosol particles and ozone, all of which result from human activity. Any effect of the sun appears to have been very small and is likely to have been offset by volcanic aerosols.

A second approach involves comparing the global mean temperature changes simulated by the same climate model with observations (above, right).

When only natural forcings were included (top panel), the observed warming after 1970 could not be explained. When only anthropogenic factors (greenhouse gases, sulphate aerosols and ozone) were used (middle panel) the recent warming was explained, but the predictions



Comparison of observed and simulated global mean temperatures (°C). The 'Natural + Anthropogenic' simulation most closely resembles the observations. The black line shows observed values.

deviated noticeably from the observations between 1940 and 1970. Only when both anthropogenic and natural forcing were combined (bottom panel) could the climate model reproduce the observed record of temperature rise. However, this good agreement between observations and model simulation should not be over-interpreted as implying that we now have a perfect climate model and a full understanding of the causes of 20th century climate change. It may be that errors within the model cancel each other.

In 1996, the Intergovernmental Panel on Climate Change (IPCC) concluded that 'the balance of evidence suggests a discernible human influence on global climate'. Recent Hadley Centre studies make us increasingly confident that human activity is a major cause of the climate change during the last 50 years.

Predictions of future climate change
From SRES emission scenarios

Recently, the IPCC published new projections of future emissions in their Special Report on Emissions Scenarios (SRES). The starting point for these is a number of 'storylines' describing the way in which the world (population, economies, etc.) will develop over the next 100 years; these are summarised in the box below. All of the SRES storylines assume a future world that is more prosperous and technologically advanced than present day. The levels of greenhouse gas emissions are generally less than the previous IPCC IS92 scenarios, especially towards the end of the 21st century. The emissions of sulphur dioxide, which produce sulphate aerosols that have a cooling effect on climate, are substantially less than in the IS92 scenarios.

The SRES scenarios are based on more-recent projections of global population and span a greater range of potential economic futures than the IPCC IS92 scenarios, including some with a significant closing of the gap between developing and developed countries.

Ways in which the world might develop; the basis of the IPCC SRES emissions scenarios

The A1 family describes a world with rapid economic growth during the 21st century and a substantial reduction in the regional variations of income per head. Global population rises during the first half of the century, peaks mid-century, then declines. New and efficient technology is rapidly introduced. The A1FI scenario sees the continuation of fossil fuels as the main energy source.

The B1 family describes a world with the same population growth as the A1 family. There are rapid changes in economic activity away from production towards a service economy. Clean and efficient technologies are introduced. Like A1, this storyline describes a convergent world.

The A2 family describes a world that remains heterogeneous with regional identity being preserved and lower income growth per head. Global population rises continuously throughout the century. The introduction of new and efficient technology is less rapid than the other scenarios.

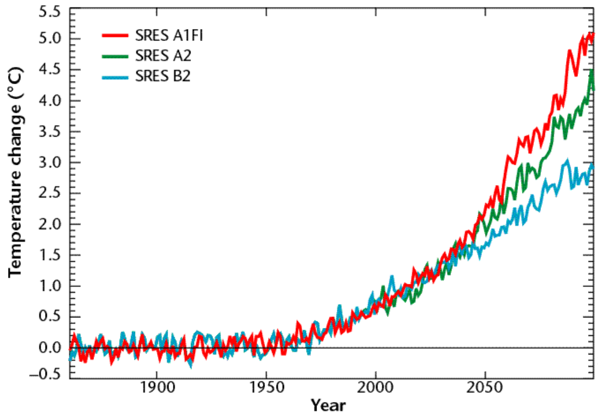
The B2 family describes a world with population increasing throughout the 21st century, but at a lower rate than A2. Levels of economic growth and technological development are less than those of A1 and B1.

Making the predictions

Predictions of future climate change were made for the A2, B2 and A1FI scenarios using the state-of-the-art HadCM3 model to simulate the response to future changes in the atmospheric concentrations of greenhouse gases and sulphur. The greenhouse-gas concentrations were calculated from the SRES emissions using separate computer models. The sulphur emissions were converted to concentrations of sulphate aerosol particles concentrations within the climate model itself.

Global mean warming

Between the present day and the end of the 21st century, we predict a warming of over 4 °C for the A1FI scenario, about 3.5 °C for the A2 scenario, and 2 °C for the B2 scenario. We expect, from simple model calculations, a warming of just under 2 °C for the B1 scenario.



Global mean temperature change (°C) relative to 1860–1890.

The spatial patterns of warming for all 3 SRES simulations (on page 8) show that surface warming is expected over most of the globe, with the largest increase of more than 10 °C in the A1FI simulation at high northern latitudes. Here, the melting sea ice causes less sunlight to be reflected and more to be absorbed at the surface leading to large warming of the region. The patterns of temperature rise also show a sizeable land–sea contrast, with the land warming approximately 80% faster than the ocean.

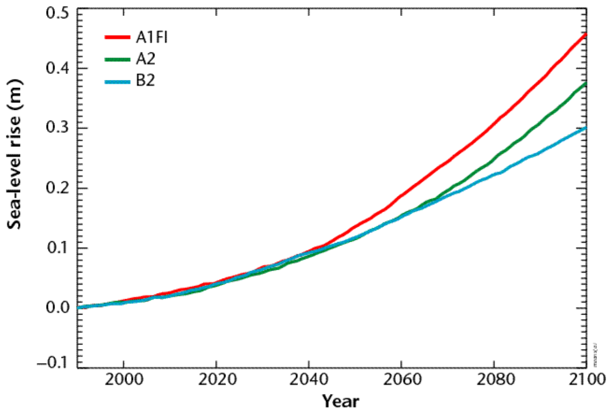
Changes in precipitation

As the climate warms, global mean precipitation (rainfall plus snowfall) is expected to increase. The predicted regional changes in precipitation are biggest (both positive and negative) in the tropics in all three SRES scenarios. During the 21st century, some land areas (notably southern Europe, southern Africa, Australia, Central America and the northern region of South America) experience a sizeable reduction in the amount of rainfall. The greatest increases in overland precipitation occur over east Asia, Central Africa, eastern South America and at high northern latitudes (on page 9). However, our confidence in the regional rainfall changes is less than that in regional temperature changes.

Predictions of sea-level rise

Sea-level rise is an important consequence of climate change. In addition to the relatively slow inundation of low-lying coastal areas as the global mean sea level rises, we expect an increase in the frequency of short-lived extreme high water events. It is these events, which are associated with storm surges, that will present the greatest threat.

The predicted rise in future global mean sea level is comprised of contributions from the thermal expansion of the ocean, the melting of glaciers and changes to the major Greenland and Antarctic ice sheets.



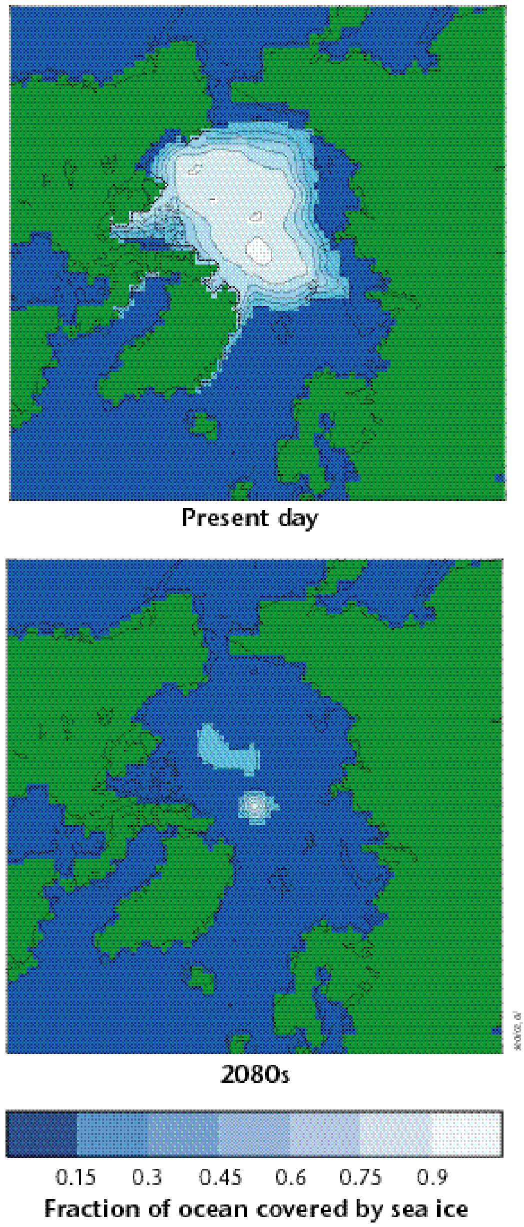
Global mean sea-level rise (m) relative to 1990.

While sea level is predicted to rise almost everywhere, there is considerable spatial variation; in some regions, the rise is close to zero, while others experience as much as twice the global average value. The predicted patterns are similar in all three SRES simulations and all show large increases in sea level in parts of the north Pacific and to the west of Greenland. Our confidence in the regional sea level rise predictions is not as great as for temperature.

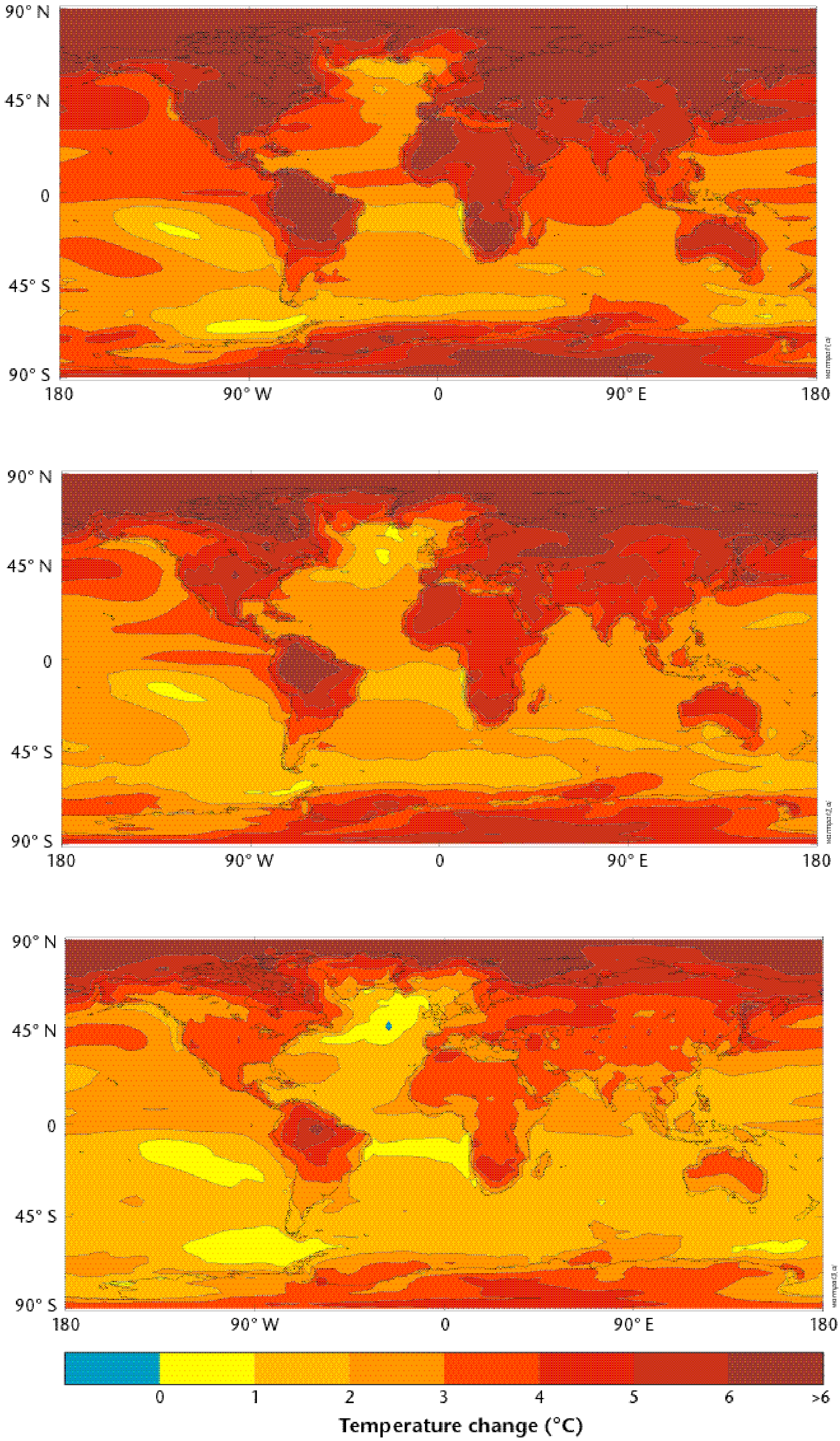
Future changes in ocean circulation and sea ice

Large amounts of heat are transported poleward in the North Atlantic Ocean by large-scale currents, the so-called thermohaline circulation. In all three SRES scenarios, the magnitude of this circulation is predicted to fall by approximately 20% during the 21st century. In the upper ocean, this corresponds to a reduction in the Gulf Stream, which, in turn, reduces the amount of heat transported poleward from the tropics. Whilst this acts to cool higher northern latitudes, the cooling is more than offset by the greenhouse effect, and both the ocean and north-west Europe as a whole warm at a substantial rate.

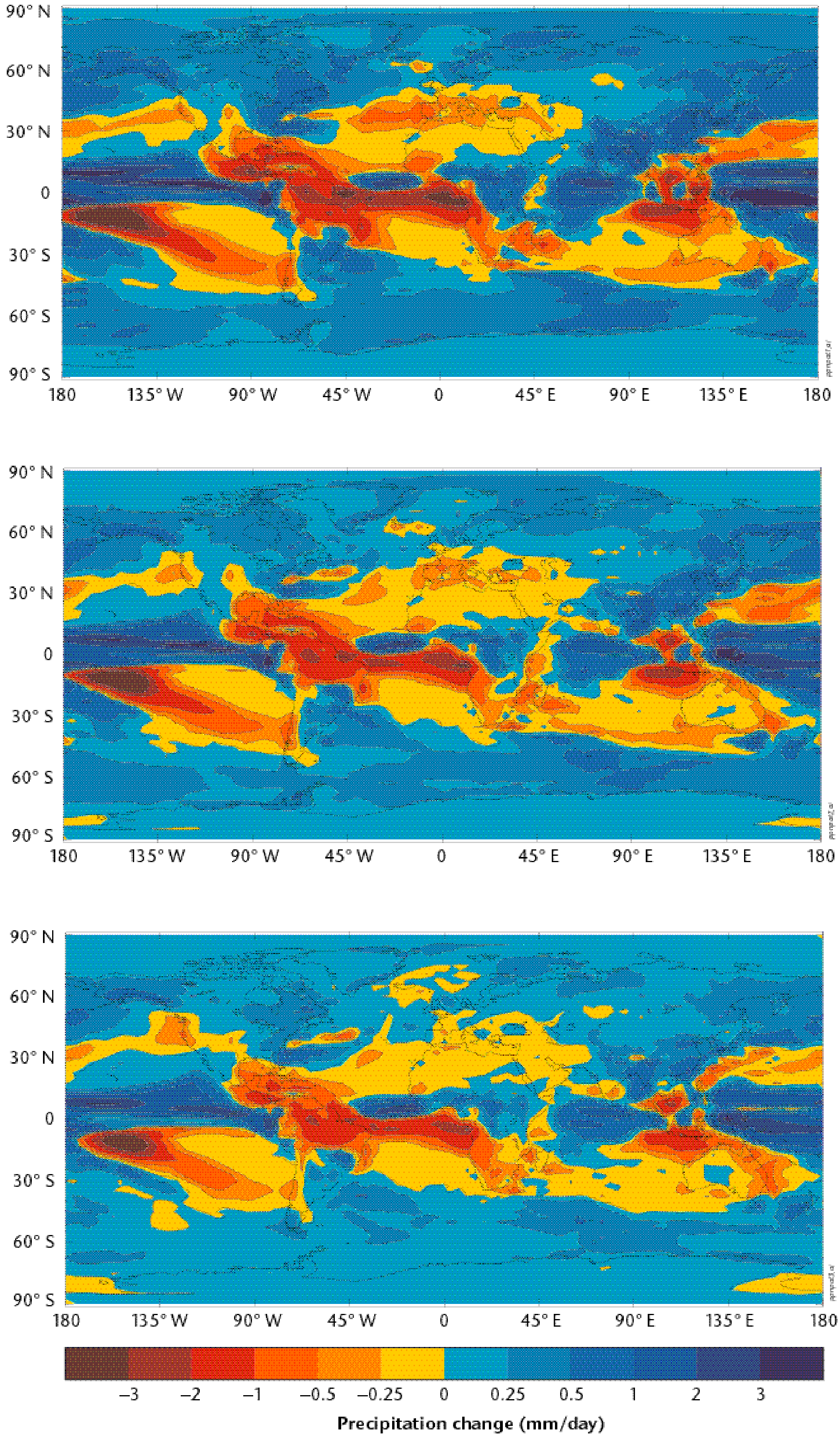
There has been recent interest in the effect of climate change on Arctic polar ice. HadCM3 predicts that, as the temperatures rise, the extent and thickness of northern hemisphere sea ice will decrease. By the end of the 21st century, the annual area of sea ice coverage is predicted to fall to around 55%, 60% and 70% of the present-day value for the A1FI, A2 and B2 scenarios, respectively. The changing pattern of sea-ice coverage is shown below for the A1FI simulation for the month of September. Even at very high northern latitudes, large reductions are predicted in the fraction of ocean area covered by sea ice. A less dramatic decrease in sea-ice amount is predicted for the southern oceans around Antarctica.



Climate model estimates of Sepember Nothern hemisphee sea-ice coverage (fractional) at present day and at the end of the 21st century for A1FI emissions scenario. The cltesring of ice around the Noth Pole in the future prediction may be an artifact of the model.



Pattern of annual average temperatue changes, 2080s relative to present day for A1FI (top), A2 (middle) and B2 (bottom)emissions scenarios.



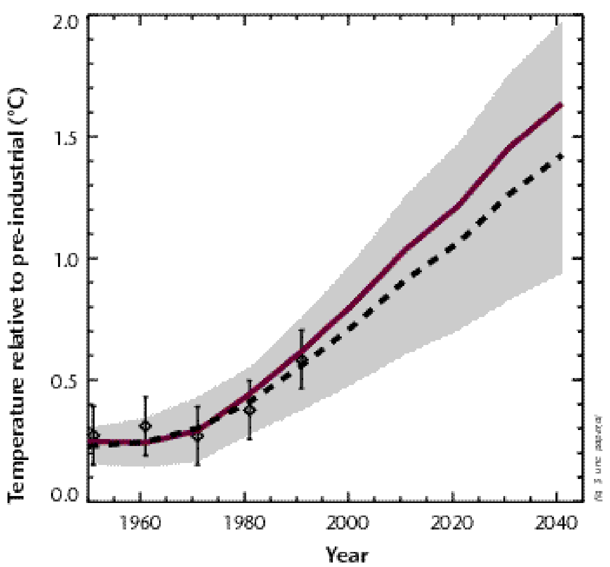
Pattern of annual average precipitation change, 2080s to present day in A1FI (top), A2 (middle) and B2 (bottom) emissions scenarios.

Uncertainty in predictions

All the predictions of climate change shown in this report, and in other publications, such as IPCC assessment reports, carry with them a range of uncertainty. Predictions of global mean temperature rise, between now and 2100, estimated for the same emissions scenario (SRES A2) using a number of different models, ranges from 1.5 °C to 5.5 °C. At smaller scales, and for changes other than temperature (for instance, rainfall) and for extreme events (such as the number of heavy rainfall days) the uncertainties are often far greater. However, estimates of uncertainty, such as those quoted by the IPCC, have been derived from expert judgement, based on the range of results from different climate models (all of which may be in error). This has been criticised as being subjective, and is not in a form that would allow risk estimates to be made.

The Hadley Centre is working towards providing objective estimates of uncertainty. We have already quantified the effect on predictions of not knowing fully the initial state of the climate system by using the same model with different initial states to produce a number of climate predictions. For many variables, such as temperature rise, the spread of predictions by the end of the 21st century is much less than the actual change.

A second source of uncertainty comes from the model itself. Recently, the Hadley Centre, in collaboration with the Rutherford Appleton Laboratory, has developed a new method to estimate the uncertainty in future climate predictions. First, a GCM is used to simulate the climate over the period 1860 to 2100. Next, the model-simulated patterns of temperature over the past 50 years are scaled to provide the best fit to those observed. The uncertainty of this fit is then carried forward to quantify the uncertainty in the predictions of climate change for next 50 years. (below)



The solid line shows a GCM prediction of temperature change. Prior to 1990, historical emissions were used. Beyond 1990, the IS92a emissions scenario was used. The dashed line shows the results of scaling the model prediction to give the best fit to the most recent 50 years of observations. The shaded region is the uncertainty estimate.

A more comprehensive approach to determining the uncertainty in climate model predictions is also being pursued. Here, the Hadley Centre is developing a large number (100 or more) climate models, each of which has a different (but plausible) representation of various aspects of the climate system (e.g. clouds, carbon cycle). These models are then run with the same emissions scenario, and give many different predictions of change in a particular climate quantity (for instance, summertime rainfall over the US Great Plains). From this, we can build up a picture of the probability of the change being at various levels, such as 10% or 20% more or less rainfall than today. By comparing the simulations of each of these climate models for the last 150 years against observations, we can judge the credibility of each of the models, and build this in to the probability estimates. The uncertainty range derived in this way will be the first to have statistical meaning, and for the first time can be used in risk analyses, such as by coastal defence planners in deciding how high to build defences.

Longer-term changes

It is important to remember that, because of the inertia of the climate system, at any time there is a substantial commitment to further future climate change, which cannot be avoided. Even if we were able to stabilise greenhouse-gas concentrations today (which would require an overnight reduction in global carbon dioxide emissions of about 60–70%), we estimate a commitment to about a further 1 °C of additional global warming, and around one metre of sea-level rise, from emissions that have already taken place over the last 100 years. As we have shown in previous reports, sea level will go on rising for many hundreds of years after greenhouse-gas concentrations have been stabilised.

Climatic effects of forestation

The Kyoto Protocol allows emissions of greenhouse gases to be offset by the planting of new forests ('Kyoto Forests'). However, will these forests actually slow down climate change?

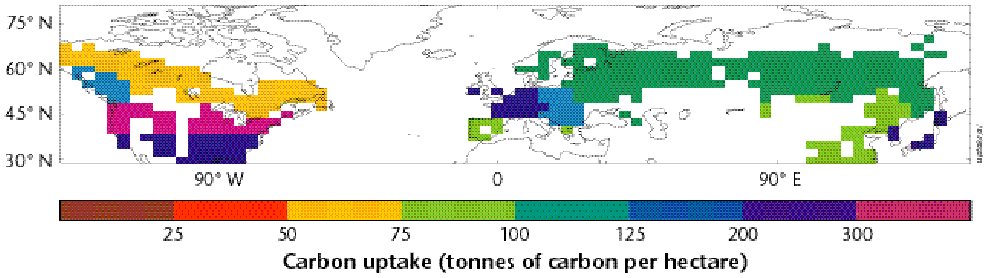
We have used the Hadley Centre climate model to quantify the effects of growing dense evergreen coniferous forests at all the locations north of 30° N that are capable of sustaining them. The results were compared with a situation in which these locations were instead used as arable cropland. The amount of extra carbon stored in the newly forested areas (the sequestration potential) is shown below (top panel).

However, trees not only absorb carbon dioxide, they have other effects on climate. In particular, because they reflect different amounts of sunshine than the underlying surface, they can alter the amount of sunlight that is absorbed. Dark green forests absorb more of the incoming solar radiation than arable cropland and will tend to warm the planet. We have estimated how much the new forests would alter the climate through this mechanism. The effect is greatest during the winter months when large unforested areas are covered in highly reflective snow, but when much of a forest canopy would remain above the snow line.

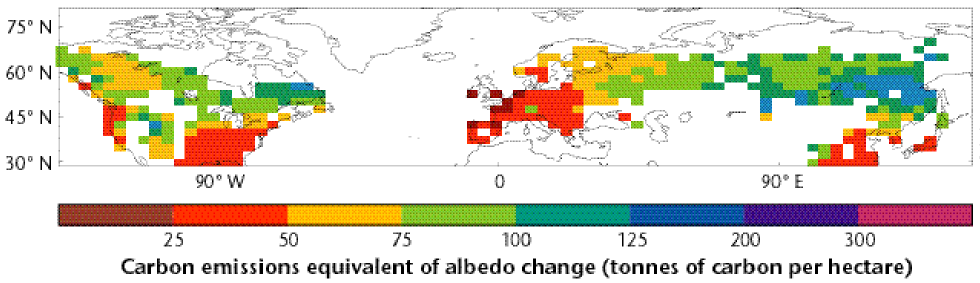
To compare the effect on climate of surface reflectivity changes with that due to the capacity of the trees to sequester carbon, the reflectivity effect has been expressed as equivalent amounts of carbon emissions. A map of the equivalent emissions is shown in the middle panel.

As expected, regions where the surface reflectivity effect is most important are at high northern latitudes in areas that have a winter covering of snow. In some boreal forest locations, the changes in reflectivity reverse the beneficial effects on climate from the uptake of carbon dioxide from the atmosphere. In many other areas, the changes in reflectivity still offset a large fraction of the sequestration potential (bottom panel).

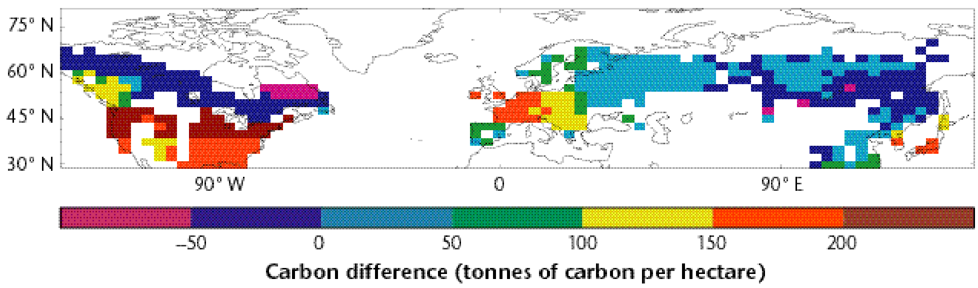
These estimates have many uncertainties, notably, the predictions of snow amount and surface reflectivity. The calculations are also for a present-day climate, and changes in temperature and atmospheric carbon dioxide concentration will alter the results. However, the results do clearly show that the beneficial effect on climate of the additional carbon sinks created by afforestation and reforestation may be, at least partially, offset by changes in the surface reflectivity as dark trees replace land cover that was lighter in colour. Consequently, in many areas, the climate benefits of planting extra trees will not be as great as their carbon 'sink' potential suggests.



Estimated carbon uptake if suitable arable land north of 30° N were to be replaced with trees.



The additional effect on climate of the changes in surface reflectivity when trees are planted on suitable arable land north of 30° N, expressed as equivalent carbon emissions.

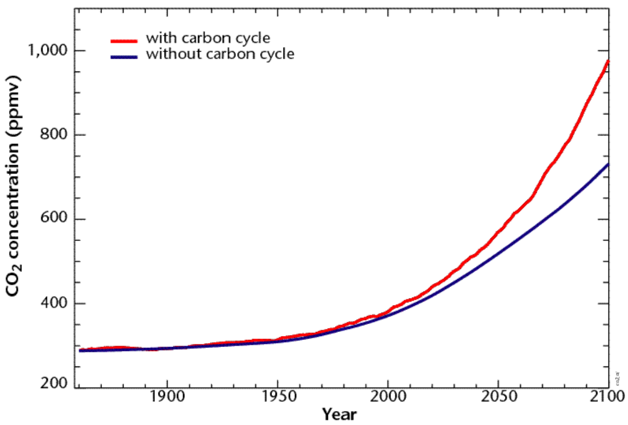


The difference between the two diagrams above. Negative values show where the net effect of planting trees is to warm climate.

Predictions of accelerated climate change
Interactions with the carbon cycle

Climate models predict that, as future atmospheric carbon dioxide concentrations increase, due to fossil fuel emissions and deforestation, the temperature of the planet will also increase. This temperature increase is currently estimated in two stages. Firstly, a model of the carbon cycle is used to calculate the future atmospheric concentrations of carbon dioxide. Secondly, the climate change is calculated using a separate global climate model. However, in reality, climate change will alter the, much larger, natural carbon cycle (see box opposite) and this can feed back on the climate change itself. Warming soils may emit more carbon, and die back of vegetation may return carbon dioxide to the atmosphere. A warmer ocean will take up less carbon dioxide from the atmosphere. Furthermore, vegetation patterns move in response to climate change. For instance, the tree line is predicted to move poleward in the northern hemisphere. For the first time, the Hadley Centre has coupled a representation of the carbon cycle to a full climate model and made predictions of climate change that incorporate climate-induced changes in the carbon cycle. This has led to some radical new insight into the climate system.

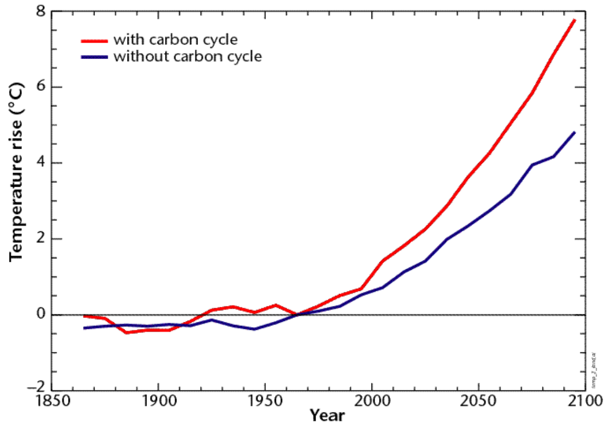
The figure below shows the atmospheric carbon dioxide concentration predicted by the coupled carbon-cycle climate model using greenhouse-gas emissions prior to present day and IPCC business-as-usual (IS92a) emissions thereafter.



Simulated atmospheric concentrations (parts per million by volume) of carbon dioxide when the two-way interaction between climate and the carbon cycle is included. For comparison, the results obtained when climate is not allowed to feed back onto the carbon cycle are also shown. Prior to 1990, historical emissions were used. Beyond 1990, emissions followed those in the IPCC IS92a scenario.

The present-day carbon dioxide concentration simulated by the model is in good agreement with observations. The slight differences are probably due in part to inaccuracies in the historical carbon emissions due to land-use changes (for instance, forest regrowth). The seasonal cycle of atmospheric carbon dioxide is also well simulated by the model.

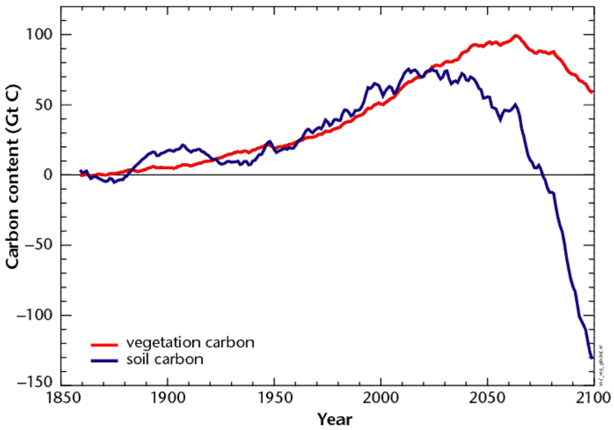
Beyond present day, the carbon dioxide concentration in the coupled carbon-cycle climate model increases faster than that predicted by previous models which neglected carbon-cycle feedbacks. As a result, when the link between the carbon cycle and climate is included, greater increases in temperature are predicted over the next century. The rise in global mean surface land temperature between 2000 and 2100 (below) is around 3 °C greater when the climate is allowed to interact with the carbon cycle, compared to the previous model estimates, which omit the link.



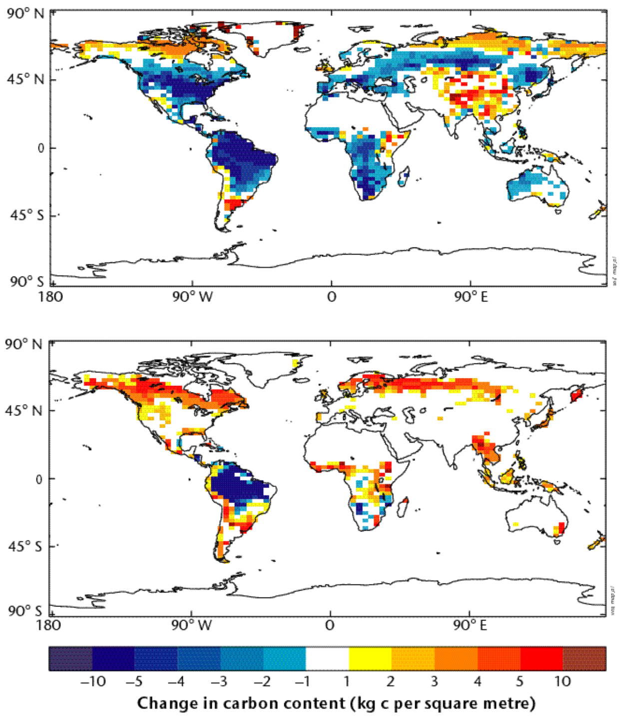
Simulated global-mean temperature rise over land with and without carbon-cycle feedback, as described in the figure left.

The model also predicts that, in the second half of this century, vegetation carbon storage in South America will begin to decline as a result of the die back of the Amazon forest, which is caused by regional warming and drying (direct anthropogenic deforestation is not included). Around the middle of the century, the land biosphere as a whole switches from being a weak sink for carbon to a strong source, mainly due to the rapid loss in soil carbon beyond 2050. In total, between the middle of the 19th century and the end of the 21st century, the combined effects of climate change and increases in atmospheric carbon dioxide concentration are predicted to reduce global soil and vegetation carbon storage by around 100 Gt C. The total global changes in soil and vegetation carbon are shown opposite. Also shown are maps of the change in terrestrial carbon content between 2000 and 2100.

Because this is the first time the two-way interaction between climate change and the carbon cycle has been included in a full climate model, there is much uncertainty in the results. Future work will look at the sensitivity of the model to the representation of vegetation, soils and ocean carbon, and improve these to increase the confidence in our predictions.



Simulated changes in the global total soil and vegetation carbon content (Gt C) between 1860 and 2100



Patterns of change in the carbon content of soil (top) and vegetation (bottom) predicted by the carbon cycle-climate model between 1860 and 2100

The carbon cycle: a simple explanation

Carbon is continuously cycled between reservoirs in the ocean, on the land, and in the atmosphere, where it occurs primarily as carbon dioxide. On land, carbon occurs primarily in living biota and decaying organic matter. In the ocean, the main form of carbon is dissolved carbon dioxide and small creatures, such as plankton. The largest reservoir is the deep ocean, which contains close to 40,000 Gt C, compared to around 2,000 Gt C on land, 750 Gt C in the atmosphere and 550 Gt C in the upper ocean. The atmosphere, biota, soils, and the upper ocean are strongly linked. The exchange of carbon between this fast-responding system and the deep ocean takes much longer (several hundred years).

The ocean takes up carbon dioxide when it is cold, at higher latitudes, and releases it near the tropics. Photosynthesis takes carbon dioxide from the atmosphere and transfers it to vegetation, while respiration releases carbon dioxide back into the atmosphere. Although natural transfers of carbon dioxide are approximately 20 times greater than those due to human activity, they are in near balance, with the magnitude of carbon sources closely matching those of the sinks. The additional carbon resulting from human activity has raised levels of atmospheric carbon dioxide by 30% over the last 150 years.

Changes in climate have a significant effect on the carbon cycle. Increases in atmospheric carbon dioxide concentration increase plant photosynthesis and the amount of carbon stored in vegetation. However, increases in temperature also lead to increases in plant and soil respiration rates, which tend to reduce the size of the terrestrial carbon store. In some regions, the changes in climate can also reduce plant photosynthesis and reduce the ability of vegetation to sequester carbon.

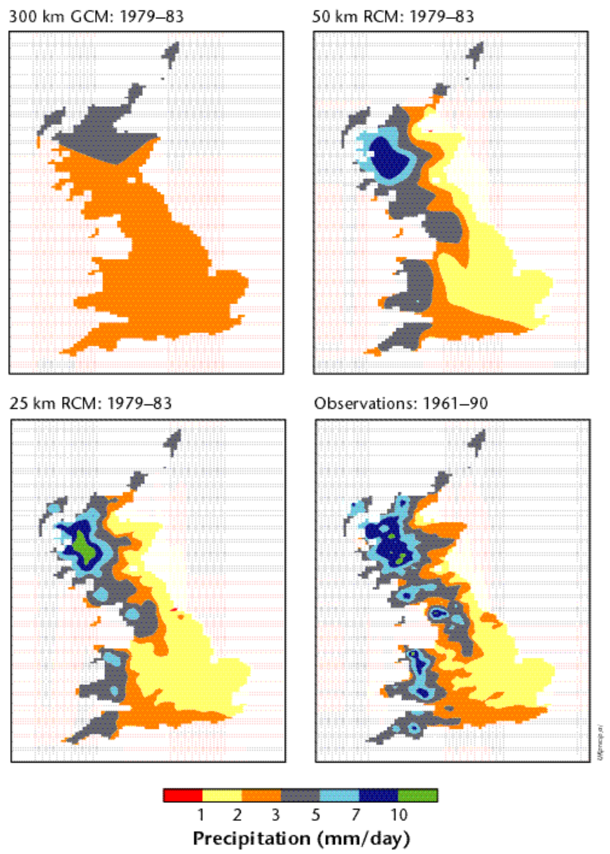
Regional climate simulations

Under Article 4 of the United Nations Framework Convention on Climate Change, individual nations are required to assess their vulnerability to climate change. Global climate models (GCMs) can provide predictions at a scale of a few hundred kilometres or more. In regions where smaller-scale features strongly affect local climate the global models fail to capture the regional detail necessary for assessment at the national level.

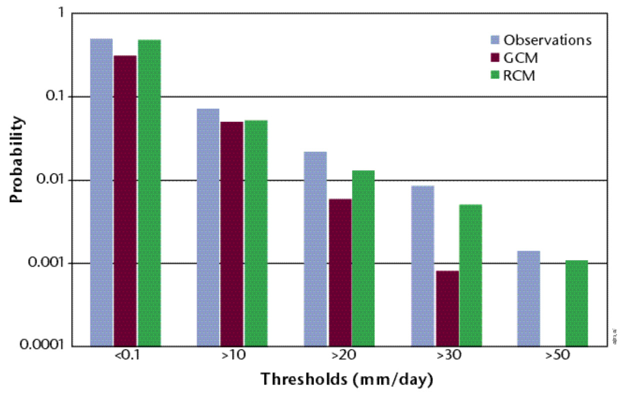
A Regional Climate Model (RCM) provides a way of downscaling the global results to the scale needed for national assessments. It provides greater geographic detail, but only covers a limited area, typically a few thousand kilometres square. The large-scale forcing at the boundaries of the RCM is provided by a global model. Because features such as mountains and coasts are better represented in an RCM, the climate associated with these features, such as mountain rainfall, is also better represented. A good example of this is given below, where the observed pattern of winter precipitation across the UK is not evident at all in a GCM, but is reproduced in the RCM. The regional models also capture small-scale weather phenomena that are unconnected with mountains or coasts. For example, the figure on page 16 shows the evolution in an RCM of a tropical cyclone in the Bay of Bengal; tropical cyclones are very poorly represented in a GCM.

This ability of the RCM to represent small-scale atmospheric processes also enables it to provide realistic simulations of localised extreme events, such as heavy rainfall, which cannot be resolved by a GCM. This is seen in simulations of daily precipitation over the Alps (below). The RCM represents well the number of dry days (less than 0.1 mm) and days with heavy rain (more than 20 mm), whereas the GCM does this poorly. We thus have more confidence in predictions of change in extremes from the RCM, than from the GCM.

However, because the RCM is forced by the GCM, it will inherit any large-scale uncertainties in predictions from the global model. Hence the RCM does not supplant the need for improved global models.



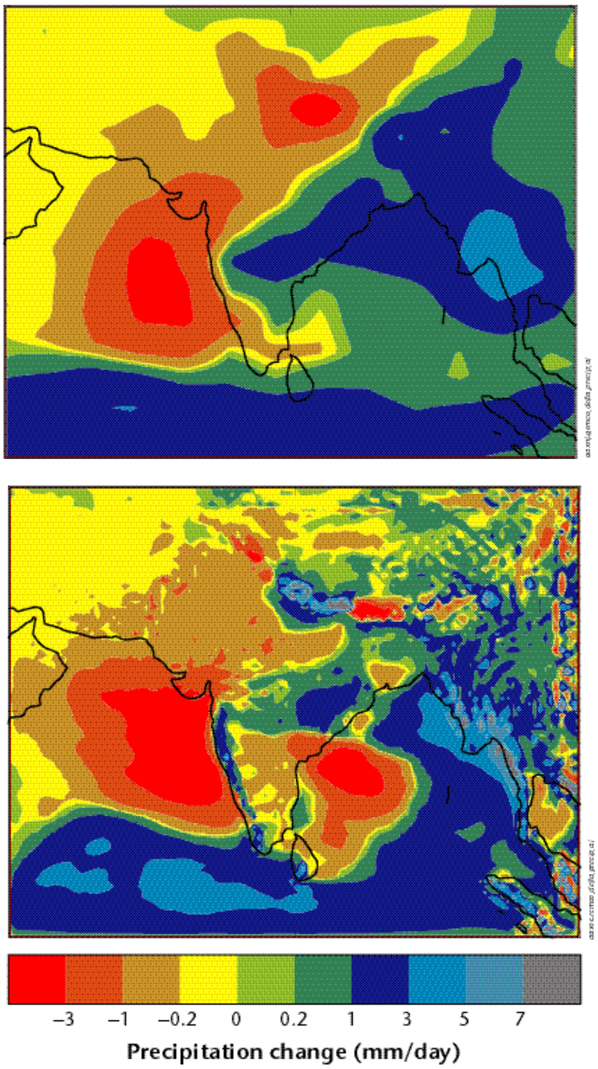
The winter precipitation over Great Britain simulated using a GCM and two RCMs, compared to observations compiled by the University of East Anglia. The RCMs capture much more of the observed detail.



The probability of daily precipitation exceeding given levels in the Alps during the winter. The RCM is able to simulate the observed extreme precipitation much better than the GCM.

Towards a portable regional climate model

There is clearly a need for the widespread availability of regional climate predictions. However, setting up a regional model currently requires a great deal of effort from an experienced climate model scientist. The Hadley Centre plans to meet this demand by building a 'portable' regional model. Interested countries could obtain the portable model (and the global model results required to drive the regional model) and run it themselves, using a top-end personal computer, as part of their commitment to assessing their own vulnerability. The transfer of technology and ownership, which would result from disseminating a portable model and the knowledge of how to produce climate predictions, would more effectively spread both scientific expertise and awareness of climate change.



The change in summer precipitation over the Indian subcontinent (mm/day) between the middle of the 19th century and the 2050s predicted using the Hadley Centre GCM (top) and RCM (bottom).

Application to India: a case study

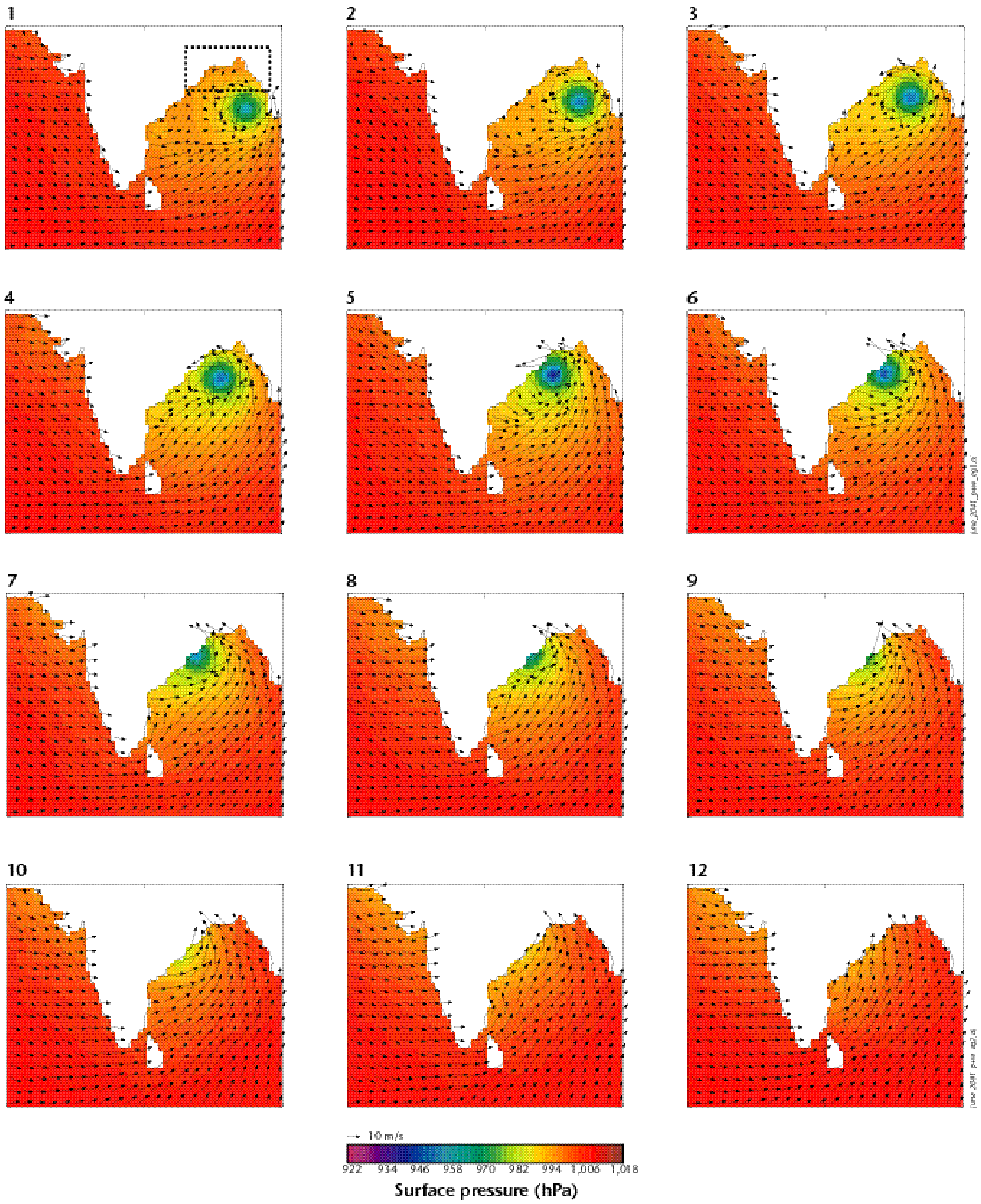
The Hadley Centre, in association with the Indian Institute of Technology, New Delhi, has also developed a regional model of the Indian subcontinent. In this region, the south Asian monsoon is central to the economy, and predicting future changes to it is a priority.

Whilst the GCM is able to reproduce the average large-scale airflow over the whole region quite well, only over the relatively flat terrain of central India does it simulate rainfall adequately. The RCM, on the other hand, does a much better job than the GCM of simulating the observed rainfall over the south-east region. Consequently predictions of changes to rainfall are also very different in the regional model; over the Western Ghats (the mountains that rise steeply from the western coast of India) the RCM predicts large increases in rainfall which are simply not seen in the GCM (See left).

As an illustration of how regional climate model results can be used to drive other kinds of model (particularly those used for local impacts assessments), the Indian subcontinent RCM is currently being used to provide the winds and air pressure necessary to simulate storm surges in the Bay of Bengal, using a surge model developed by the Proudman Oceanographic Laboratory. Storm surges are temporary increases in water level, above the tide and mean sea level, which result from low pressure and strong winds acting on the surface. The behaviour is particularly pronounced in shallow regions, such as on the continental shelf in the Bay of Bengal. In this region, which is difficult to protect because the coastline is a river delta, the resulting coastal flooding often leads to considerable loss of life and property.

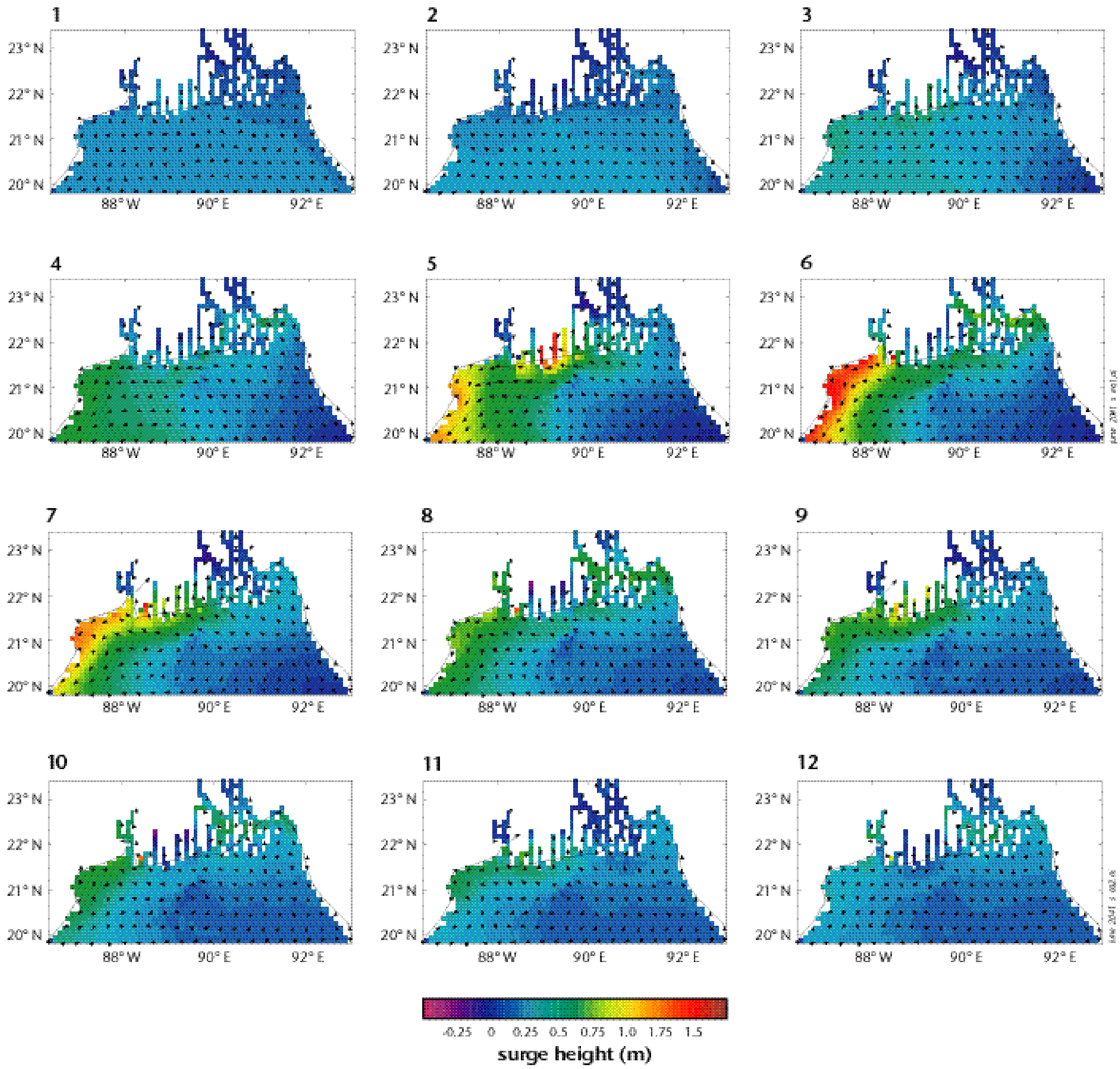
The cyclone simulated in the RCM (page 16) gives rise to changes in water levels, which are shown on page 17. A positive storm surge is seen to form in the north-west of the Bay of Bengal as the cyclone passes over the region. The surge predictions are critically dependent on the ability of the RCM to accurately predict cyclone frequency, track and strength. The results from 20 years of such simulations, and 20 years of predictions for the middle of this century, are being used to analyse how frequently large storm-surges occur along the coastline, and to predict how this might change in the future. This sort of research can only be done using an RCM, as current global models are not able to realistically simulate cyclones.

Modelling the evolution of a cyclone



The evolution of a tropical cyclone in the Bay of Bengal, simulated using the Hadley Centre RCM. The panels show the surface pressure (hPa) and wind arrows (m/s) at 6-hour intervals. The dotted line in panel 1 shows the region covered by the surge model simulations opposite.

Modelling the evolution of a storm surge



The evolution of a storm surge in the Bay of Bengal, simulated using a storm-surge model driven by the simulated cyclone pressure and winds shown left. The panels show the storm-surge height, relative to tide and mean sea-level, at 6-hour intervals.

Hadley Centre Staff: October 2000

Lisa Alexander, Robert Allan, Richard Allan, Jim Arnott, Helene Banks, Martin Best, Richard Betts, Daniel Bleaken, Cyndy Bunton, Andrew Bushell, Mick Carter, Claire Cooper, Peter Cox, Denise Cresswell, Douglas Cresswell, Paul Davison, Xiaosu Dia, Chris Durman, Ian Edmond, John Edwards, Richard Essery, Chris Folland, Nicola Gedney, Margaret Gordon, Chris Gordon, Allan Grant, Dave Gregory, Jonathan Gregory, Dave Griggs, Jake Hacker, David Hall, David Hassell, Rosalyn Hatcher, Diane Hatcher, Chris Hewitt, Emma Hibling, Briony Horton, Debbie Hudson, William Ingram, Geoff Jenkins, Tim Johns, Cathy Johnson, Colin Johnson, Andy Jones, Chris Jones, Richard Jones, Gareth Jones, Kumar Kaushal, Roy Kershaw, John King, Jeff Knight, Joe Lavery, Evelyn Leung, Linda Livingston, Jason Lowe, Gordon Lupton, Ian Macadam, Gill Martin, Kathy Maskell, Mark McCarthy, Ruth McDonald, John Mitchell, Steve Mullerworth, James Murphy, Steven Murray, Maria Noguer, Elisabeth str m, Alison Pamment, Anne Pardaens, David Parker, Vicky Pope, Nicky Rayner, Graham Rickard, Mark Ringer, Malcolm Roberts, David Roberts, Mark Rodwell, Karen Rogers, William Roseblade, David Rowell, Cath Senior, David Sexton, Karl Shepherdson, Tony Slingo, Doug Smith, Steven Spall, Peter Stott, Rachel Stratton, David Tan, Ruth Taylor, Simon Tett, Robert Thorpe, Alan Thorpe, Linda Tse, Tristan Tuftnell, Paul van der Linden, Michael Vellinga, Mark Webb, Jean Weber, Stuart Webster, Paul Whitfield, Alistair Williams, Keith Williams, Damian Wilson, Simon Wilson, Richard Wood, Margaret Woodage, Stephanie Woodward, Peili Wu.

This report is also available at:

www.metoffice.gov.uk/research/hadleycentre/pubs/brochures/B2000/index.html